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MULTI-ORBIT MISSION BY PSLV-C3 AND FUTURE LAUNCH OPPORTUNITIES☆

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Abstract

Polar Satellite Launch Vehicle (PSLV), the Indian operational launcher, completed its sixth flight PSLV-C3 on 22nd October 2001 from Sriharikota Launch Range (SHAR). It was the fifth successive successful mission, proving the reliability and versatility of the medium lift vehicle developed by Indian Space Research Organisation (ISRO). In this flight, along with the primary remote sensing satellite TES of ISRO, two auxiliary payloads, viz BIRD from M/s DLR, Germany and PROBA from M/s Verhaert, Belgium were also deployed. While Technology Experimental Satellite (TES) and Bispectral and Infrared Remote Detection (BIRD) were injected into a nominal 568 km circular sun synchronous polar orbit (SSPO), PROject for On-Board Autonomy (PROBA) was released at a higher altitude into a 568×638 km elliptical orbit. An orbit raise manoeuvre utilising guidance margin reserve propellant available in the fourth stage was performed prior to PROBA injection. The three axis stabilised orbit raise burn was executed by the axial RCS thrusters firing in off-modulated mode. The high precision achieved in the orbital parameters of all three satellites has validated the navigation, guidance and control scheme implemented. The successful realisation of this multi-orbit mission by ISRO has opened up opportunities and mission flexibility for small satellite launches on PSLV, which has a provision to carry two 120 kg class satellites as passenger payloads. This paper describes the specific strategies adopted and their outcome in PSLV-C3 to perform the multi-orbit mission. The on-board systems and ground segment features in terms of both hardware and software elements, including the Preliminary Orbit Determination (POD) scheme for PROBA deployment, are described. Further developments on PSLV with respect to high-performance third stage (HPS3) and single engine fourth stage (L1) towards performance enhancement and mission flexibility are presented. Forthcoming missions and commercial launch opportunities on PSLV are highlighted.
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Keywords: Multi-orbit mission; PSLV; POD

1. HISTORY/BACKGROUND

Polar Satellite Launch Vehicle (PSLV), the operational launcher of India, has so far made six flights, the first three being developmental and the latter three on operational missions. PSLV-C3, the third operational flight that took off on October 22, 2001 from Sriharikota Range (SHAR), the spaceport of India, carried the main payload, Technology Experimental Satellite (TES), and along with it two auxiliary satellites, viz BIRD from M/s DLR, Germany and PROBA from M/s Verhaert, Belgium (Fig. 1).

This is the second multi-satellite mission performed by PSLV, the earlier PSLV-C2 flight in May 1999 deployed Indian OCEANSAT and two passenger payloads, viz KITSAT-3 from SaTReC, South Korea and DLR-TUBSAT from Technical University of Berlin/DLR.

The history of PSLV development programme and earlier flight experience are given in Refs. [1,2].

The speciality of PSLV-C3 mission was the requirement of one of the auxiliary payloads ‘PROBA’ to be injected into a higher orbit. While the primary satellite TES and the first auxiliary satellite BIRD were put into a sun synchronous polar orbit (SSPO) of 568 km circular, PROBA was released into an elliptical orbit of 568×638 km after an orbit raise manoeuvre.

The software and hardware aspects of implementing the multi-orbit mission, including the strategy to

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confirm the PROBA injection elements, are briefly described in this paper.

2. PSLV-C3 CONFIGURATION

PSLV-C3 adopted a standard operational flight configuration with six S9 strapon motors augmenting the first stage solid booster S-139. The PL-40 second stage with 40 t of hypergolic propellant combination of UDMH and N2O4, the S7 solid third stage motor and the L2 Liquid upper stage with MON/MMH combination constituted the rest of the vehicle. The vehicle is three axis stabilized throughout the flight regime and on-board navigation, guidance and control processor implements closed loop guidance till PS4 engine cut-off when the satellite injection vector is attained.

Figure 2 gives the overall PSLV configuration and identification of vehicle sub-systems. The characteristic parameters of PSLV are in Table 1.

Fig. 1. PSLV-C3 lift-off from Shriharikotta on 22nd October 2001.

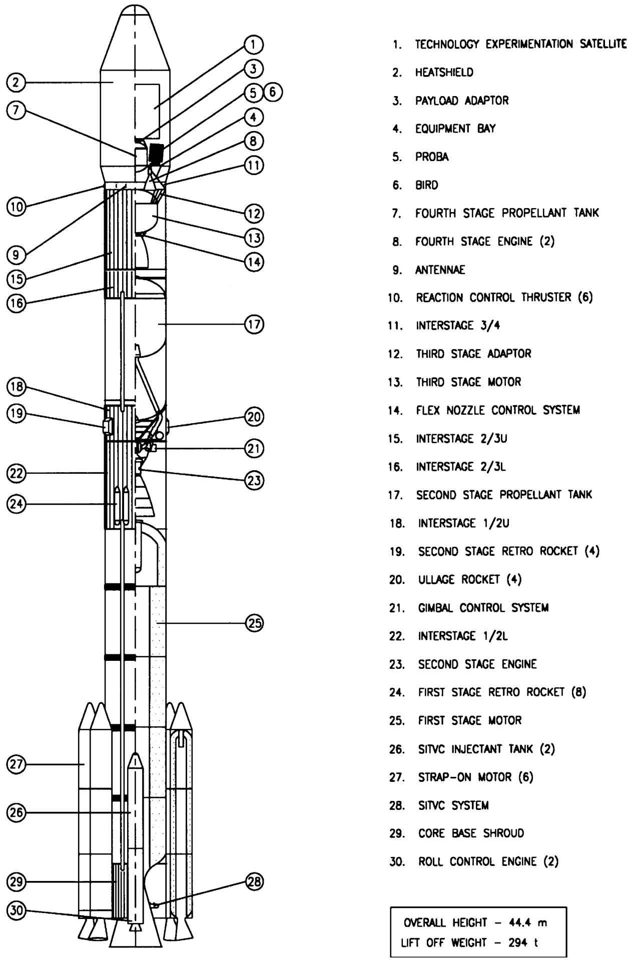

Fig. 2. PSLV-C3 configuration.

2.1. The Fourth Stage (PS4)

The PSLV fourth stage (PS4), which injects the satellite into orbit, is a liquid propulsion system employing hypergolic propellant combinations of Mixed Oxides of Nitrogen (MON) and Mono Methyl Hydrazine (MMH). It has two pressure-fed, regeneratively cooled engines of 7 kN thrust operating in tandem. The stage is attitude stabilized and steered through engine gimballing, which provides control moments about pitch, yaw and roll axes.

Control during non-powered phase is through bi-propellant reaction control thrusters of 50 N rating. The RCS engines are configured in two pods of three thrusters each as depicted in Fig. 3. As can be seen, while the yaw control is by the axial thrusters, pitch and roll control is by the two pairs of tangential thrusters working on sharing algorithm. These thrusters operate in pulse mode to sustain the attitude angle limits as per command.

Table 1
Overall characteristics of PSLV

Dimensions	Strapon motors (PSOM-S9)	Stage-1 (PS1-S138)	Stage-2 (PS2-PL40)	Stage-3 (PS3-S7)	Stage-4 (PS4-L2)
Length (m)	11.3	20	12.5	3.6	2.6
Diameter (m)	1.0	2.8	2.8	2.0	2.0
Mass					
Propellant (t)	6×9.0	138.0	40.5	7.3	2.1
Gross (t)	66.0	168.0	45.8	8.4	3.0
Structure Materials	High strength steel	High strength steel	Aluminium alloy	Composite	Titanium
Propulsion					
Number of engines	6 motors	1	1	1	2
Propellant	HTPB based solid	HTPB based solid	UDMH and N2O4	HTPB based solid	MMH and MON
Average thrust (kN)	677	4430	724	324	2×7.4
Attitude control					
Pitch (P)	Not provided	SITVC (P)	E/n gimballing (P and Y)	Flex nozzle control (P and Y)	E/n gimballing in thrusting phase
Yaw (Y)	Not provided	SITVC (Y)			
Roll (R)	SITVC	RCS (R)	Hot gas thruster (R)	RCS of PS4 (R)	RCS (coasting)

2.2. The Payload Interface

The main satellite TES sits on top of the PS4 stage over a conical composite payload adaptor with standard ϕ937 band-clamp interface. In addition, interfaces are provided to carry two auxiliary spacecrafts 120 kg class by modifying the Vehicle Equipment Bay (EB) layout to create two 40° sector slots on the EB deck. This arrangement came into force in PSLV-C2 flight, which was the first multi-satellite mission by PSLV.

The auxiliary payloads are interfaced through IBL 298 jettisoning systems based on spring actuated ball-lock mechanism developed by the Indian Space

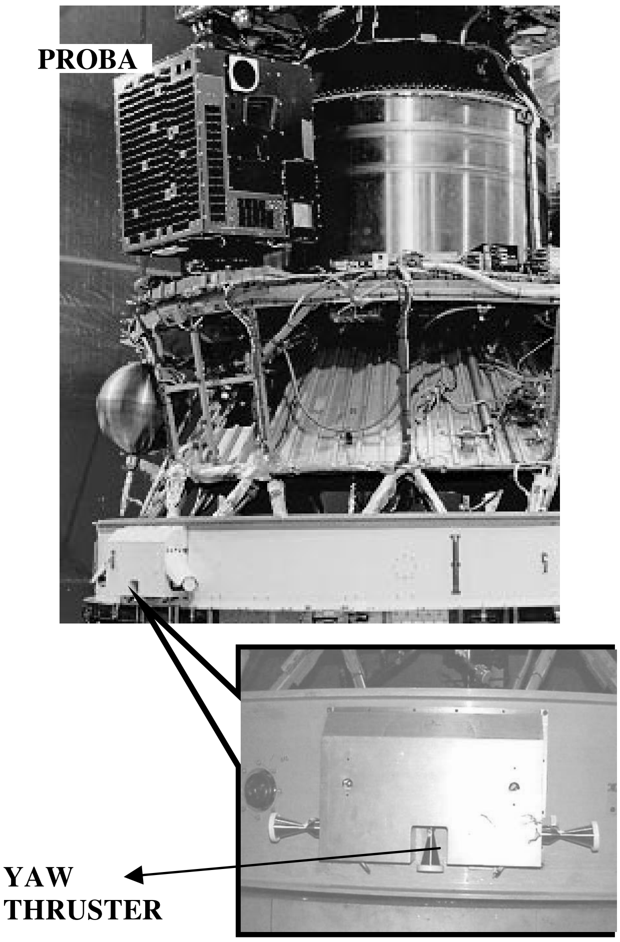

Fig. 3. RCS thruster configuration.

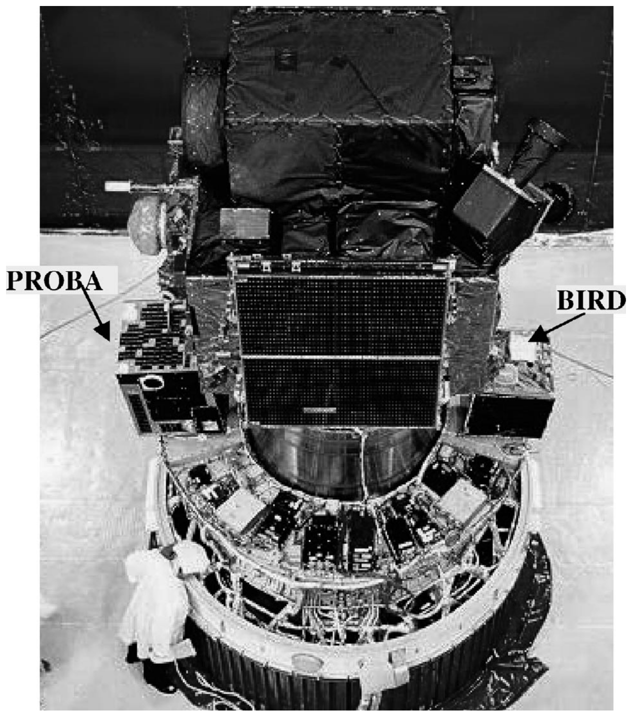

Fig. 4. Spacecrafts in PSLV-C3 mission.

Research Organisation (ISRO) for deploying micro-satellites.

The mounting configuration of the three satellites TES, PROBA and BIRD inside C3 vehicle fairing is depicted in Figs. 4 and 5.

2.3. Payload Separation Systems

The PROBA satellite is mounted on the P+ sector at an offset from vehicle axis with an outward tilt of 5°, which is introduced in the adaptor interfacing with the EB deck. The BIRD satellite is on the diametrically opposite sector with identical interfaces.

The separation system is based on a 'Ball Lock' mechanism wherein a set of hardened steel balls lock the inner race with the outer ring with match drilled radial holes. Redundant pyro thrusters rotate the outer retainer ring to cause radial escape of balls through aligned holes, thereby effecting the release of the inner ring attached to the satellite. The jettisoning velocity is provided by a set of helical compression springs symmetrically located at the interface.

3. PAYLOAD AND MISSION SPECIFICATIONS

The main payload for PSLV-C3 was TES remote sensing experimental satellite from ISRO satellite centre weighing 1110 kg. The mission was to inject this satellite into a sun synchronous polar orbit of 568 km altitude at an inclination of 97.67°.

The second payload was BIRD, acronym for Bispectral and Infrared Remote Detection, a milestone mission in the small satellite programme of DLR, Germany with an objective of demonstrating the scientific and technological value and programmatic feasibility of advanced technologies in a small satellite. This satellite weighed 92 kg and orbit specifications of the main payload TES was accepted for BIRD mission.

The third payload was 'PROBA', acronym for PROject for On-Board Autonomy, an ESA funded programme with Verhaert Design and Development, Belgium as the prime contractor. The primary objective of this spacecraft is the demonstration of on-board operational autonomy. Apart from this, PROBA also implemented remote sensing payloads in terms of an earth observation imager and a high-resolution camera.

During interface discussions, the PROBA team put forth their preference for an orbit at a higher altitude, different from the TES orbit specifications. After feasibility studies, it was mutually agreed that PROBA will be deployed into a 568×638 km elliptical orbit at 97.79° inclination.

4. TRAJECTORY DESIGN AND FLIGHT SEQUENCE

PSLV-C3 adopted a standard flight sequence of core booster and four strapons igniting at lift-off and remaining two strapons motors ignited in air at T+25s to limit the aerodynamic loads on the vehicle. The vehicle cleared the atmosphere adopting an open loop steering programme optimised and biased towards mean wind profile over launch site. The payload fairing separated during the second stage thrusting phase when the dynamic pressure falls to acceptable value. The first, second and third stage burnouts were sensed in flight to initiate further transition events. Between third and fourth stage regimes, there is a long coast during which the vehicle gains altitude. The closed loop guidance, which was initiated during second stage burn, implemented optimal steering of the vehicle and also decided the fourth stage ignition time and vector. The PSLV-C3 flight profile is pictorially depicted in Fig. 6.

On realising desired injection conditions for the main payload TES, on-board computer issued PS4 thrust cut-off command. TES was separated at 57 s from PS4 cut-off after executing a −80° turn in yaw. The BIRD spacecraft was ejected 40 s later, after a +40° yaw recovery. Subsequently, PS4 stage with PROBA was re-oriented back to original head-on attitude in preparation of the orbit raise manoeuvre (Fig. 7).

The above injection sequence was finalised based on standard analytical procedures for multi-satellite deployment mission, which were developed and validated during the previous mission on PSLV-C2 (detailed in Ref. [2]).

The mission analysis performed were specifically to address the following aspects:

- Coupled load analysis for loads and frequency imposed on vital spacecrafts components.
- Separation dynamics simulation to ensure re-contact free deployment of spacecrafts under worst-case conditions.
- Limits of rotational rates imparted on to the spacecrafts at separation.

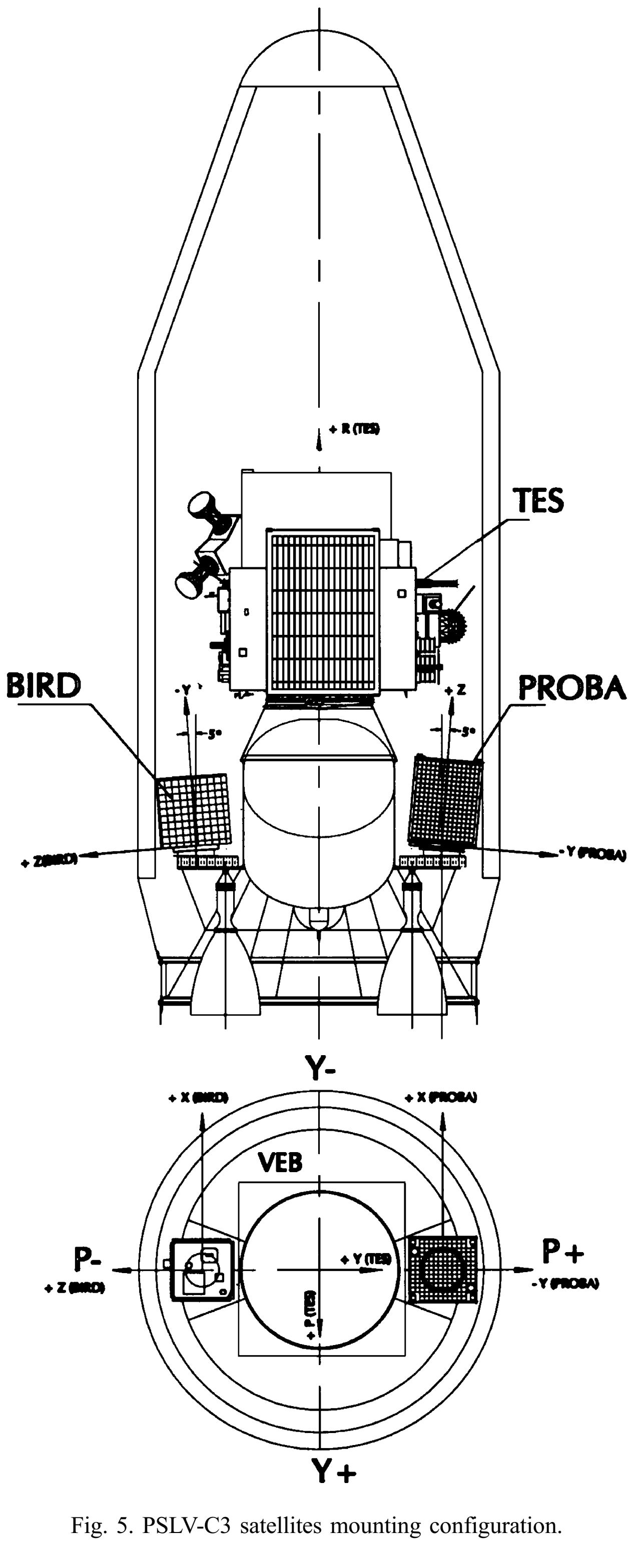

Fig. 5. PSLV-C3 satellites mounting configuration.

- Long-term propagation of relative distances between the multiple bodies in orbit to ensure minimal separation.

A detailed Mote Carlo analysis was carried out considering dispersion of various parameters such as

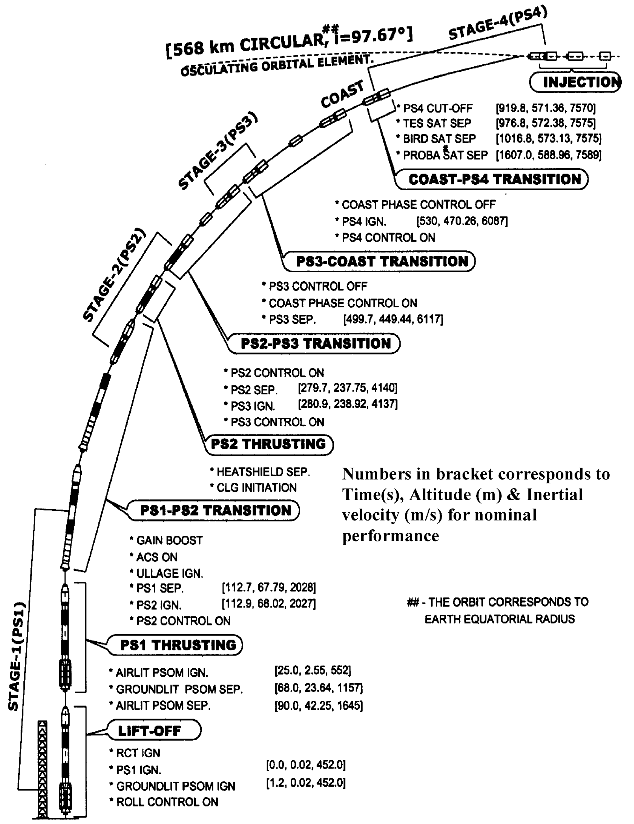

Fig. 6. PSLV-C3 flight sequence.

mass properties, geometrical tolerances, jettisoning spring energy, etc., to establish adequate margins.

5. PROBA ORBIT RAISE MANOEUVRE

As stated in Section 3, PROBA mission team preferred injection into a higher elliptical orbit of 568×638 km with corresponding inclination change to 97.79°.

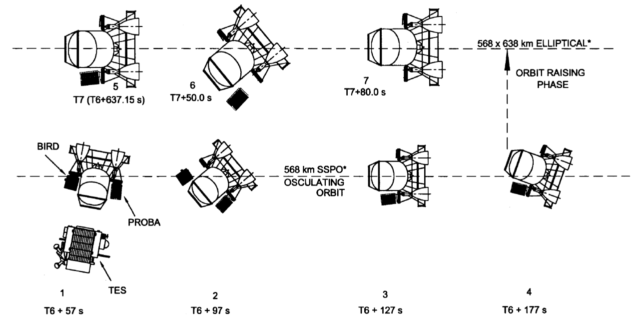

Fig. 7. Spacecraft separation sequence. Description of sequence: (1) Separation of TES after yaw turn of −80°. (2) Separation of BIRD after a yaw turn of +40°. (3) Yaw turn by +40° back with PROBA. (4) Beginning of PROBA orbit raise after re-orientation in pitch and yaw for optimal guidance angle. (5) PS4 stage orbit raised to 568×638 km. (6) Separation of PROBA after a turn of −40°. (7) Yaw turn back by +40° for PS4 stage.

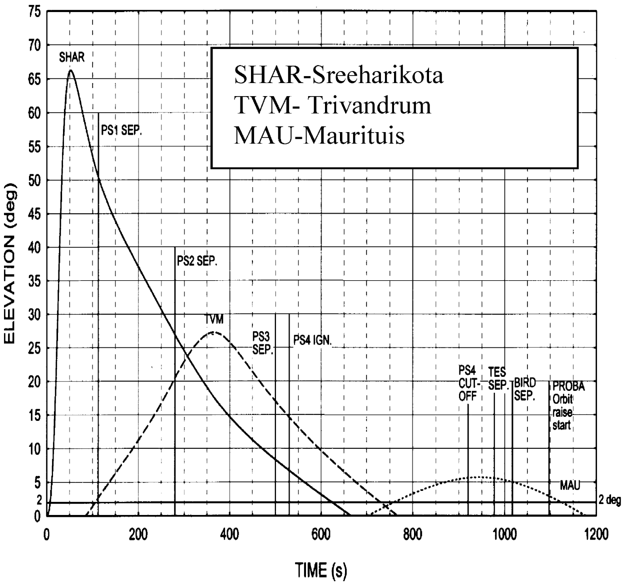

Fig. 8. Visibility from ground stations.

Though restart of PS4 propulsion system was a possible option to impart the ΔV of 150 m/s to implement this orbit change, due to adverse centre of mass positioning of PS4+ PROBA composite and the twin engine configuration, controllability was an issue to be resolved. Consequently, it was decided to utilise the two axial RCS thrusters designed for PS4 yaw control to achieve this velocity gain. This scheme of utilising the attitude control thrusters for imparting net velocity of stage demanded the change of yaw control law from on-modulated mode to off-modulated mode during this orbit raise manoeuvre. Also, the operating mixture ratio of these 50 N bi-propellant thrusters was shifted to more benign levels of 1.2 from 1.4 to improve the thermal margins during the continuous burn. These thrusters were also re-qualified on ground for the modified duty cycle employed for the first time in PSLV-C3 flight.

Some of the mission analysis issues addressed prior to the flight were:

- Propellant reserve available in PS4 after TES/ BIRD deployment under performance dispersion limits for various lower stages.
- Yaw thrusters plume geometry during orbit raise burn and its impact on TES and BIRD already in orbit.
- The thermal effects of continuously burning yaw thrusters on PS4 stage elements.
- The extension of launch phase duration from 1200 s nominal to about 1700 s in this mission and its overall implications on the vehicle Equipment Bay, specially with reference to onboard power margins, navigation and guidance system performance, etc.

6. NAVIGATION, GUIDANCE AND CONTROL

PSLV uses Redundant Inertial reference and navigation system and on-board processor for generating guidance parameters as well as steering commands in flight. The Inertial sensors and the processor packages are housed in the annular Equipment Bay (EB) on the fourth stage (PS4). The vehicle flight sequencing functions are implemented through on-board computer, suitably interfacing with the hardware. Separation of spent propulsive stages is by on-board sensing and Real Time Decision (RTD) functions.

PSLV clears the atmospheric phase of flight using and optimal open loop steering profile, which is time based. Closed loop guidance is initiated 5 s after Heat Shield jettisoning during PS2 flight regime. Guidance commands are generated in PS2/PS3 thrusting phase based on "Velocity to be gained" steering scheme. Then a coast phase guidance algorithm predicts the optimal coast duration and also generates steering commands during PS3/PS4 transition coast to orient the PS4 at the time of ignition.

An explicit guidance algorithm generates the final optimal steering commands during PS4 thrust phase terminating in PS4 thrust cut-off command when the injection parameters for the primary satellite, viz TES, is reached.

For PROBA orbit raise phase, which was a new element in C3 flight, a simplified guidance scheme was developed and implemented. The algorithm generates commands to the required direction and

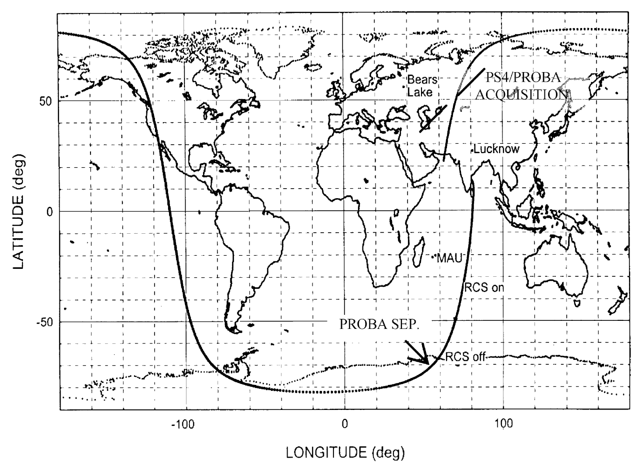

Fig. 9. Ground trace of PSLV-C3.

then computes the 'Time to Go' for achieving the desired target conditions based on the rate of semi major axis variation. In this way, the altitude gain and inclination change for PROBA were simultaneously achieved in an optimal way within the constraints of on-board reserve impulse available in PS4 stage. Guidance cut-off flag was generated based on time-to-go once the desired target ellipse for PROBA was achieved.

Validation of closed loop guidance for PSLV-C3 was carried out for the month of launch mean wind biased trajectory on integrated simulation test beds, for nominal and various off-nominal vehicle performance bounds. System failure modes and open loop salvage profiles were also exercised during the above simulations. Totally, about 30 performance dispersion cases and six failure modes simulations were studied to confirm the robustness of Closed Loop Guidance (CLG) design.

The CLG algorithm achieved the target orbit for PROBA for all performance deviation cases with positive propellant reserve after PS4 thrust cut-off.

7. TRACKING AND PRELIMINARY ORBIT DETERMINATION (POD)

PSLV-C3 vehicle was equipped with two C-band transponders and one S-band range and range rate transponder on-board.

A network of Indian ground stations, SHAR-1, SHAR-2, Trivandrum, Mauritius, Bangalore and Lucknow, provides telemetry, tracking and command support. The confirmation of separation of TES and BIRD and POD was determined from the telemetry data received from Mauritius station. The separation of PROBA occurs beyond the visibility range of Mauritius station. The separation event indication and the inertial parameters are stored on-board in a Data Storage Unit (DSU) package and transmitted over the Lucknow station in the first pass after a long visibility gap. Other international stations taking part in this mission were Bears Lake, Biak and Weilheim for the initial TES operations. Data transmissions between ground stations were carried out through both satellite links and terrestrial links for real time display and POD.

The elevation angles and visibility profile for PSLV-C3 trajectory from different ground stations during flight evolution is given in Fig. 8. The ground trace of C3 flight with satellite deployment events is shown in Fig. 9.

7.1. Telemetry and Tracking

As can be seen, while TES and BIRD separations are visible from ISRO down range ground stations at Mauritius, PROBA deployment takes place outside the range of this station. The PROBA orbit raise manoeuvre start and about of 30 s of orbit raise phase can be tracked from Mauritius. As such end of PROBA

Table 3
Achieved orbits of spacecrafts

Spacecraft	Predicted	Achieved
TES		
Apogee (km)	573.7	576.55
Perigee (km)	565.8	558.65
Inclination (deg)	97.67	97.77
BIRD		
Apogee (km)	572.6	576.73
Perigee (km)	565.8	558.69
Inclination (deg)	97.67	97.77
PROBA		
Apogee (km)	637.9	656.47
Perigee (km)	565.7	572.39
Inclination (deg)	97.79	97.82

Table 2
PSLV-C3 flight sequence

Pre-flight (from T0) (s)	Event	Post-flight (s)
0.0	PS1 ignition	0.02
112.7	PS1 separation	111.46
156.7	Heat Shield separation	155.46
278.74	PS2 separation	280.8
498.28	PS3 separation	500.34
520.42	PS4 ignition	546.06
915.38	PS4 thrust cut-off	912.42
972.38	TES separation	969.42
1012.38	BIRD separation	1009.42
1092.38	PROBA orbit raise start	1089.42
1521.40	PROBA orbit raise ends	1591.06
1571.40	PROBA separation	1641.06

Table 4
Yaw rates on stage and spacecraft at separation

	On stage (deg/s)	On spacecraft (deg/s)
TES		
Predicted	1.7–3.5	0.1–1.67
Measured	0.71	1
BIRD		
Predicted	7.8–9.7	1.2–11.8
Measured	6.65	4.5
PROBA		
Predicted	8.7–10.7	2.2–6.86
Measured	7.45	5.8

orbit raise manoeuvre and separation of PROBA could not be confirmed in real time from Mauritius.

Since access to the vehicle transmitter was available only after about 60 min time gap when the PS4 with EB comes over Lucknow ground station during the first orbital pass, it was decided to make use of on-board Data Storage Unit (DSU) to capture 25 s of salient on-board parameters relevant to confirm PROBA deployment vector and retransmit the same when the spent stage was over Lucknow ground station. Since visibility over Lucknow ground station is feasible only after about 4000 s from PROBA separation event, to conserve the on-board power, all instruments and transmitters except Inertial systems and DSU were switched off and transmitters were switched on again using an on-board sequencer.

7.2. Preliminary Orbit Determination (POD)

POD for PSLV-C3 mission involved activities for acquiring data from different sources and processing them to assess the orbital parameters of the three satellites, TES, BIRD and PROBA. Extensive studies were conducted to plan the POD process and the scheme was finalised.

The data sources for POD were:

- Inertial Navigation system parameters through telemetry received at the Mauritius ground station and subsequently the DSU captured data received at the Lucknow and SHAR-I ground stations.
- Tracking data of range, range rate and angles from Mauritius (for TES).
- Tracking data of range, range rate and angles from Lucknow (for PS4)
- RITM data from Bearslake.

POD of TES and BIRD satellite was carried out using tracking data received from Mauritius. POD for PROBA was based on telemetry data received at Mauritius on the performance parameters during the start of the orbit raise burn. The orbit raise phase was extrapolated on ground using the same guidance algorithm implemented on-board to predict the trajectory propagation. Based on this computation, look angles for PROBA/PS4 acquisitions were transmitted to Bearslake, Lucknow and SHAR stations.

The POD for PROBA was confirmed based on the telemetry data from DSU received at the Lucknow as well as the tracking data. The state vector of PROBA at injection was provided to the satellite agency.

8. C3 FLIGHT OUTCOME

PSLV-C3 lift-off occurred precisely at 10:23 h IST on 22nd October 2001 as planned with out any hold during countdown. The performance of all the propulsive stages were close to the nominal and the net velocity gained before PS4 ignition was marginally higher than the pre-flight nominal. The thrust cut-off command for PS4 stage was issued by guidance when the orbital injection conditions of TES were achieved. Actual burn duration of PS4 was less than the pre-flight nominal due to the over performance of the lower stages. Consequently, the left out propellants in PS4 was higher than the pre-flight nominal, but within the dispersion limits predicted.

The TES separation followed by separation of BIRD occurred as per planned manoeuvres. For PROBA orbit raise phase, the stage was oriented to the optimal attitude by on-board guidance in pitch and yaw. Velocity addition by firing the yaw RCS thrusters in off-modulated commenced as planned. The vehicle was kept at the desired attitude throughout this phase by guidance and the RCS thrusters. As residual propellant at PS4 cut-off was higher than the pre-flight nominal, the resultant stage mass increase made the RCS firing for the orbit raise 43.5 s longer than the pre-flight nominal of 457.5 s. The salient mission flight events are listed in Table 2.

The POD for TES and BIRD were made based on the inertial system data received through telemetry at Mauritius station. For PROBA, POD was made based on the inertial system data received for the 50 s of visibility of orbit raising phase from Mauritius station and also predicted the look angles for the Lucknow and SHAR ground stations to receive the delayed telemetry data from the on-board DSU to confirm the PROBA separation. Using the look angles provided based on the above data; PROBA was first acquired by Kiruna station confirming the separation and subsequent powering of the spacecraft. The Lucknow and SHAR station acquired the spent PS4 stage and received the telemetry data confirming the safe separation of PROBA. SHAR station also acquired the PROBA spacecraft in its first pass.

The achieved orbits vs. the pre-flight specifications are given in Table 3.

The separation environments of the spacecrafts were benign. The separation induced rates on the spacecrafts and stage were within predicted bounds. Maximum induced rates were in yaw direction due to the off-centre mounting of the spacecrafts in yaw

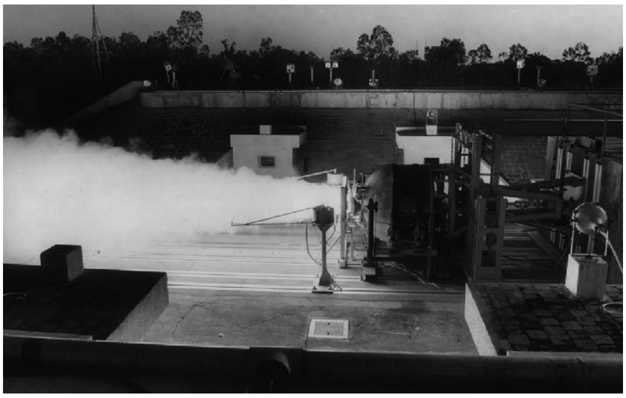

Fig. 10. HPS3 static test.

Fig. 11. Composite PS3 stage structure.

plane. Table 4 gives the bounds of rates predicted on spacecraft and stage (nominal value and worst-case rates considering residual rates on stage/spacecraft composite, dispersions in mass, centre of gravity and spring energy) and the measured rates on stage and spacecrafts.

9. FUTURE PERSPECTIVE

The next flight of PSLV-C4 is on a Geo-synchronous Transfer Orbit (GTO) mission of deploying the Indian Meteorological satellite METSAT, weighing 1050 kg into a $200\times36{,}000$ km orbit. The PSLV performance has been enhanced (Ref. 3) by the induction of more powerful high-performance third stage motor (HPS3), with higher propellant loading, less inert mass and improved specific impulse. In addition, upper stage weight reduction through the adoption of composite structures for the inner branch of HPS3 and PS4 has also been implemented in C4 (Figs. 10 and 11).

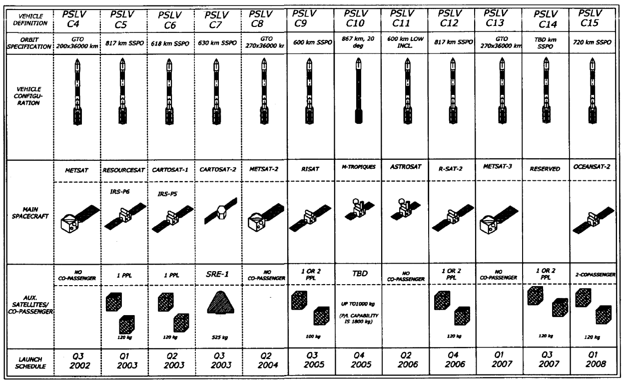

Fig. 12. PSLV launch manifest.

With the above improvements, the PSLV can carry 1500 kg satellite to sun synchronous polar orbit of 600 km reference altitude. It is proposed to further augment this to 2000 kg through the induction of more powerful extended strap-on motors.

With the above payload capabilities PSLV flights will continue to have slots for two auxiliary satellites of 120 kg each. Some of these flights will have Dual Launch Adaptor (DLA) for carrying two primary satellites in a stack. The induction of single engine compact liquid stage (L1) will enable PS4 restarts and multiple burns to inject the different satellites in their respective orbits specified.

PSLV launch manifest projection for the coming years indicating the micro-satellite mission opportunities are given in Fig. 12.

10. CONCLUSION

With the string of five successful flights, Indian PSLV has matured into a reliable operational launcher for medium lift missions. The multi-satellite/multi-orbit missions executed flawlessly in last two flights enhanced the versatility of this vehicle. PSLV has unique proven interface for micro-satellites. The forthcoming GTO mission and the proposed dual launch mission in the near future will establish PSLV as a very cost-effective option in the launch vehicle market.

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